SOME IMPLICATIONS OF A BASAL DETACHMENT STRUCTURAL MODEL FOR OLYMPUS MONS. Patrick J. McGovern and Sean C. Solomon, *Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA, mcgovern@dtm.ciw.edu.*

Summary. A basal detachment model for the formation of the Olympus Mons aureole and basal scarp [1] has important implications for the elastic lithosphere thickness (T_e), hydrological conditions, and structural evolution of the volcano. In this model, landslide material (the aureole) fills the flexural moat, obscuring the pre-slide surface and thus invalidating earlier lower bounds on T_e at Olympus Mons [2]. Several lines of argument suggest that T_e may be less than these bounds. Formation of this basal detachment requires liquid water (pore fluid) and may require a thick, areally extensive deposit of material with low hydraulic diffusivity (such as clay). Deep parts of the detachment may lock due to fluid loss from compaction, yielding a central edifice with a welded base surrounded by landslide deposits over a detached base. Conditions in a basal detachment may provide favorable habitats for autotrophic organisms.

Introduction. The edifice of Olympus Mons is more than 600 km in diameter and rises about 27 km above the datum. A scarp up to 6 km high defines the base of the edifice, which is surrounded by an aureole of disrupted terrain extending for hundreds of kilometers. Several workers [3-5] have suggested that the aureole consists of large landslide structures. The basal scarp, in this view, consists of the coalesced head scarps of these landslides [3]. Structures of such magnitude were thought to be uncommon around large terrestrial intraplate volcanoes until sonar imaging revealed many such structures around volcanoes of the Hawaiian [6] and other [7] volcanic chains. A basal detachment in pelagic sediments atop the oceanic crust is thought to allow formation of flank landslides at Hawaii [8, 9]. By analogy, we [1] proposed that a partial basal detachment at Olympus Mons could account for the observed aureole and scarp structures. Here we examine several implications of such a model.

Elastic Lithosphere Thickness. *Thurber and Toksöz* (1978) [2] used stresses and displacements calculated from elastic flexure models to constrain the elastic lithosphere thickness (T_e) at Olympus Mons. For values of $T_e < 150$ km, they found large downward displacements and tensional stress levels sufficient to cause faulting at the surface of the lithosphere surrounding the volcano. They argued that since both large depressions and surface fracturing are not observed around the volcano, $T_e > 150$ km. However, terrestrial intraplate volcanoes also lack such evidence of flexure. For example, the lithosphere beneath the Hawaiian Islands is known to be deflected beneath the load (from seismic and gravity data [10, 11]), but this deflection is filled with landslide deposits derived from the edifices [6]. No fractures surrounding the Hawaiian Islands have been seen in bathymetric data or sonar imaging [e.g., 6] (although small fields of flood basalts near the flexural arch [12] are indirect evidence for horizontal tensile stress in the lithosphere).

From flexure models for an edifice roughly the size of Hawaii (radius = 180 km , height = 9 km), using the axisymmetric thick-plate flexure formulation of [13] and including effects of buoyancy from the ocean and loading from moat filling material, the criterion of [2] (peak tensile stress no larger than 100 MPa) yields a lower bound for T_e at Hawaii of 80 km. The elastic plate thickness for Hawaii is constrained by gravity and seismic studies, however, to the range 25-45 km [10, 11]. It is likely that moat-filling deposits at Hawaii obscure flexural deformation and fracturing of the lithospheric surface. If the Olympus Mons aureole is analogous to the large slumps and slides that fill flexural moats around Hawaii and other large volcanoes on Earth [1], then the aureole deposits fill the moat around Olympus Mons, concealing the surface of the lithosphere. Graben that may have formed there will not be able to propagate coherently upward through the kilometers-thick layer of fragmented material which constitutes the moat fill. In addition, for flexure models of an Olympus-Mons-sized edifice (see below), the radial distance of peak σ_{rr} is about half the farthest extent of the moat; formation of graben beyond the moat edge is unlikely. Lithospheric fracturing around Olympus Mons, therefore, will be hidden by the aureole deposits which fill in the topographic moat. The lack of observed graben and deep topographic deflections, therefore, does not constrain T_e at Olympus Mons.

Detachment Properties and Formation. The formation of a basal detachment requires a specific set of conditions. The detachment beneath Hawaiian volcanoes is rooted in the layer of abyssal clay sediment emplaced before volcano formation [8, 9]. The low hydraulic diffusivity (proportional to permeability) of clay sediments allows the generation of high pore fluid pressures as the sediments consolidate from the growing volcanic load [14]. The pore pressure facilitates slip along the sediment layer. Terrestrial volcanoes lacking a sufficiently thick basal clay layer lack evidence for basal detachments [15]. The presence of clay minerals on Mars has been inferred from chemical analysis and spectroscopic studies of the surface [e.g., 16]. Heat flux from the interior of Mars allows the presence of liquid water at depths of a few kilometers [17]. Thus, the conditions required for a Hawaiian-style basal detachment may exist beneath Olympus Mons.

The rigid-wedge limit-equilibrium analysis of *Iverson* (1995) [14] constrains the conditions under which a flank section of Olympus Mons can become unstable (i.e., capable of forming the aureole/basal scarp structure by landsliding). This analysis considers the balance of forces on a wedge of volcano flank, including groundwater seepage forces resulting from groundwater head gradients and consolidation of porous layers. Failure will occur when the shear force resolved along the potential slip surface (wedge base) exceeds the frictional strength. For reasonable values of fault friction angle ϕ (30°), surface slope ψ (5°), and detachment slope θ (-10°),

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flank instability requires a very restrictive set of conditions: a basal layer more than several hundred meters thick with extremely low hydraulic diffusivity (10^{-11} m^2/s), and > 70% groundwater saturation of the wedge. Such conditions are unlikely to be met without invoking a large reservoir of liquid water near the flanks of Olympus Mons, to provide for groundwater saturation and deposition of an areally extensive and thick clay sediment layer (previous to volcano formation). Sporadic formation of the Oceanus Borealis [18] could provide such a reservoir. This requirement may be relaxed, however, by the addition of flexurally-induced shear stresses to the force balance of the above analysis. These stresses result from the radially inward deformation of the lithosphere surface during flexure (they therefore increase with decreasing T_e). The destabilization of large sectors of Olympus Mons may require a large contribution from such stresses, favoring a lower range of T_e values than previously proposed [2].

Edifice Structure. The depth profile of the postulated basal detachment may exert an important influence on the structure of Olympus Mons. The proximal region of the shield contains circumferential terraces that have been interpreted as thrust faults [19]. This observation and the absence of characteristic detached-base features on the shield itself led to the suggestion that the core of Olympus Mons experiences a welded basal boundary, in contrast to the detached basal boundary beneath the aureole (presumably terminating near the basal scarp radius) [1]. Loss of pore fluid in the detachment may be responsible for this difference. The increase of confining pressure with depth will tend to close pore spaces and expel pore fluid. Models of the distribution of porosity with depth in a dry regolith [17] yield a self-compaction depth (at which porosity is 1% of its surface value) range of about 8.5-11 km, although for a wet crust these values may increase by about a third [17]. If a fluidized basal detachment is brought below the self-compaction depth by flexural subsidence, the resulting loss of pore fluid may prevent further detachment slip. Deflections are greatest beneath the proximal regions of the volcano and increase with volcano growth; the detachment should thus gradually lock up from the center outwards.

Deflections from an Olympus Mons load [13], including the load of moat-filling material, are shown (Fig. 1) at the edifice axis ($r = 0$) and edge ($r = 300$ km) as a function of T_e. The deflection (i.e., detachment depth) at the edifice edge is within or near the range of self-compaction depths given above, a result consistent with interpretation of the edifice edge (i.e., the basal scarp) as the innermost extent of detachment activity. The radius of the basal scarp may thus be controlled by the radius at which the deflection reaches the depth where water is expelled from the detachment. The difference between axial and edge basal depths decreases with increasing T_e (Fig 1). At $T_e > 100$ km, this difference (several km) may not be enough to account for the strong difference between proximal (shield) and distal (aureole) behavior, unless the depth interval of dewatering is similarly small. At $T_e < 100$ km, the large differences in edge and axial deflections could easily account for the difference in proximal and distal
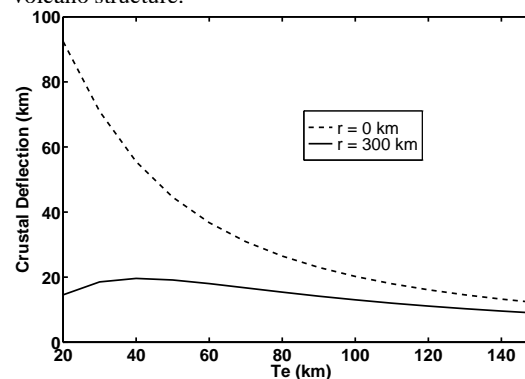
volcano structure.

Figure 1. Deflections from loading by an edifice with radius = 300 km and height = 25 km vs. T_e.

Refuge for Life? Conditions required for the existence of a basal detachment are also conducive to the existence of subsurface life. The discovery of possible remnants of Martian lifeforms in meteorite ALH84001 [20] has driven speculation about sites where life may continue to exist on Mars. The basal detachment model proposed above requires the presence of liquid water deep within the volcano, where temperatures will be elevated due to the above-average thermal gradient and magmatic heat. Olympus Mons, and more generally the Tharsis region, have likely been a source of thermal and chemical energy for a large fraction of the planet's history. The deep flanks of Olympus Mons are shielded from exposure to ultraviolet radiation, extreme cold, and other surface conditions harmful to life. The flanks of Olympus Mons thus constitute a site favorable to the long-term maintenance of life on Mars, perhaps in the form of lithoautotrophic organisms such as those discovered in Columbia River basalts [21]. The proposed landslide structure of the distal flanks implies that evidence of this potential deep refuge for life may be found at or near the surface of the Olympus Mons aureole.

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